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Final Report

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Radio Astronomy with Microspacecraft

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Jet Propulsion Laboratory

Abstract and Contents

Abstract

A dynamic constellation of microspacecraft in lunar orbit can carry out valuable radio astronomy investigations in the frequency range of 30 kHz–30 MHz, a range that is difficult to explore from Earth. In contrast to the radio astronomy investigations that have flown on individual spacecraft, the four microspacecraft together with a carrier spacecraft, which transported them to lunar orbit, form an interferometer with far superior angular resolution. Use of microspacecraft allows the entire constellation to be launched with a Taurus-class vehicle. Also distinguishing this approach is that the Moon is used as needed to shield the constellation from RF interference from the Earth and Sun.

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Radio Astronomy with Microspacecraft

Primary Contributors and Contributions

Doug Bernard:	information on attitude control dynamics, considerations, and options
Gaj Birur:	information on loop heatpipes
Willard Bollman:	information on how needed TCM ΔV scales with trans-lunar injection error and time after injection
David Collins:	task management / study leadership; all system and subsystem design concepts; all engineering analyses (not identified elsewhere); and final report generation / editing / review
Richard Cowley:	information on power utilization by bang-bang hydrazine attitude control thrusters
Bob Glaser:	information on the capabilities of structures
Dayton Jones:	information on radio astronomy, radio interferometers, and the ALFA proposal; the content of Appendix A (Science); and final report review
Ken Kelly:	information on antenna characteristics and design concept for medium-gain downlink antenna
Alex Konopliv:	information on navigation, lunar orbit stability, Lunar Prospector, and SELENE
M J Mahoney:	information on radio astronomy
Warren L Martin:	information on Deep Space Network capabilities
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David Morabito:	downlink rate calculations
Barry Nakazono:	information on numerous propulsion components and propulsion options
Morgan Parker:	information on low-minimum-impulse, low-mass hydrazine thrusters
Richard Webster:	information on line/bolt cutters
Chen-wan Yen:	trans-lunar trajectory analysis and design; calculation of all deterministic ΔV magnitudes; Earth-Moon and Moon orbit insertion trajectory plots; and final report review
Larry Young:	information on radio ranging systems
Sam Zingales:	information on the state of the art in transponders and the feasibility of miniature transponder development

Also, Gene Burke, Warren Frick (OSC), Don Nieraeth, Jonathan Perret, and Jeff Srinivasan contributed other information.

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Radio Astronomy with Microspacecraft

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Radio Astronomy with Microspacecraft
Overview

Mission Baseline

Science: 30 kHz–30 MHz radio astronomy

Observatory:
a separated-spacecraft interferometer
that uses the Moon as an RF shield

Launch Vehicle Class: a Taurus/STAR 37FM with 63" fairing

Trajectory to the Moon: direct (< 5 days)

Interferometer Dynamic Array:
Five spacecraft in synchronized, 200-km lunar orbits
with 2 separated microspacecraft in each of two
3° orbit planes and 1 carrier spacecraft in a 6° plane

Two 5-m astronomy antennas
extend from the 0.4-m diameter shell
of each spacecraft

In lunar orbit, each spacecraft rotates at
1 RPM about a line perpendicular to the ecliptic

	Each Micro-spacecraft	Carrier spacecraft
Available Power	53 W	123 W
Stabilization	Spin	3-axis
Data Storage	384 MByte	384 MByte
Telecom with Earth	X-Band	X-Band
Shell Height	49 cm	133 cm
Block Redundancy	No	Yes
Dry Mass (+35%)	13 kg	48 kg
Propellant	Ammonia	Hydrazine
Wet Mass	14 kg	128 kg

Executive Summary

- The electromagnetic spectrum of interest in radio astronomy spans many decades of frequency, but the lower portion of this range, from 30-kHz to 30-MHz, is largely unexplored due to the difficulties presented by the ionosphere and interference from radio sources on Earth. Some measurements have been made at the lower frequencies from spacecraft but with only very poor angular resolution.

- While the relatively small apertures available with microspacecraft currently limit their use in radio astronomy to investigation of phenomena with strong radio signals, there are strong sources in the 30-kHz to 30-MHz range, and a number of important scientific investigations can be conducted in this regime with collections of microspacecraft.

- One feasible implementation would utilize lunar orbits. Launched by a single Taurus-class (or possibly smaller) vehicle, four microspacecraft would be transported to the Moon and placed in orbit by a carrier spacecraft, which would then become the fifth measurement platform. Three slightly different orbit planes would be used with the carrier in one plane and two separated microspacecraft in each of the others. All orbits would have the same period, and phasing would be adjusted to establish the dynamic constellation. Nominal separation distances between spacecraft would range from 50 km to 250 km.

- The interferometer thus formed would have extremely good angular resolution and also have the benefit of periodic shielding from both the Earth and Sun. (Data would be recorded over the shielded far side of the Moon and sent to Earth when the Moon would not block the signal.)

Objective, Relevance, and Scope

- Study Objective
  - Consider the potential value and feasibility of using constellations of microspacecraft for radio astronomy.
- Relevance to NASA, Code S, and JPL
  - Radio astronomy investigations from Earth in the 30-kHz to 30-MHz range are difficult due to problems with the ionosphere and interference from radio sources on Earth.
  - Observations from space are not troubled by the ionosphere and offer the possibility of reduced interference from Earth.
  - Good angular resolution is important in many of the investigations and is available if the effective aperture is very large, which is potentially practical using an interferometer formed with multiple spacecraft.
  - Using microspacecraft offers the possibility of implementing the interferometer with both lower launch cost and lower recurring spacecraft cost.
- Study Scope / Limitations Due To Study Resource Constraints
  - The study met its objective through development of a high-level microspacecraft mission design concept that is consistent with valuable radio astronomy investigations. Highly detailed analyses were beyond the scope of this small study.

Introduction

- Early work in this study revealed an existing concept, a MIDEX proposal[1], to carry out radio astronomy investigation using an interferometer composed of microspacecraft. Some of the basic characteristics included:

  Science - Investigations in the 30-kHz to 30-MHz range
  Location - ≈ 1E6 km from Earth in distant retrograde orbit
  Configuration - Microspacecraft in ≈100-km spherical shell centered on carrier spacecraft
  Number - 16 microspacecraft, 1 carrier spacecraft
  Wet Mass - ≈ 614 kg total (≈ 29 kg/microspacecraft, ≈ 150 kg for carrier)
  Launch - Delta II (7425)
  Tracking - Continuous with DSN 11-m network

- With that background, it was decided to develop a concept for a simpler microspacecraft mission that would have fewer spacecraft and lower launch mass. Basic characteristics for the final concept developed include:

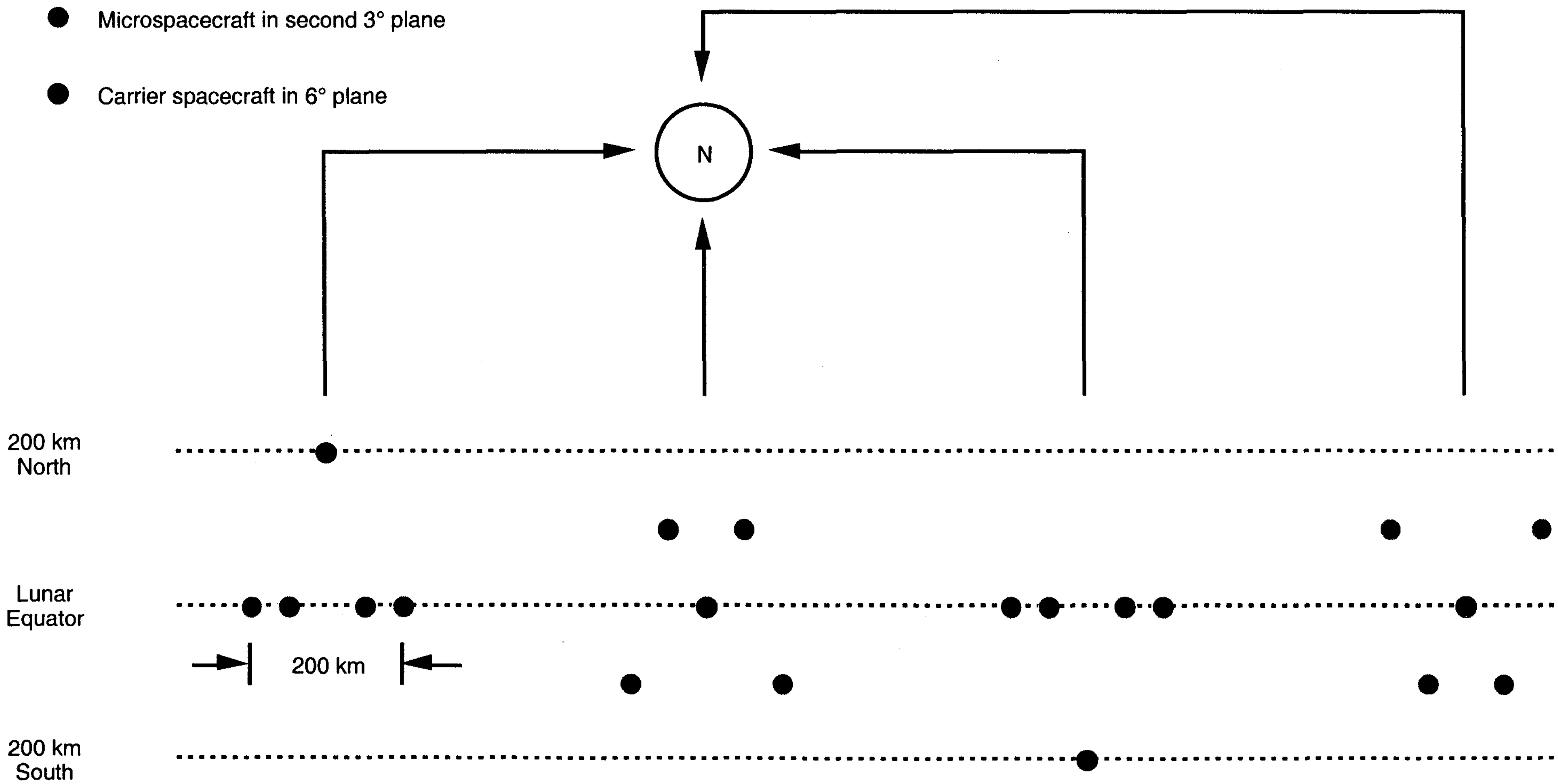
  Science - Investigations in the 30-kHz to 30-MHz range
  Location - < 4E5 km from Earth in lunar orbit
  Configuration - Microspacecraft and carrier in ≈ 250-km dynamic array
  Number - 4 microspacecraft, 1 carrier spacecraft
  Wet Mass - ≈ 184 kg total (≈ 14 kg/microspacecraft, ≈ 128 kg for carrier)
  Launch - Taurus/STAR 37FM (or possibly smaller vehicle)
  Tracking - ≈ Monthly with DSN 34-m network (after array deployment and checkout)

[1] In this report, superscripts that follow an alphabetic character refer to references listed on Page 60.

System Description and Summaries

Approximate Array Configurations
(at times separated by a quarter orbit each)

- Microspacecraft in first 3° plane
- Microspacecraft in second 3° plane
- Carrier spacecraft in 6° plane



Science Investigations Summary

- The radio astronomy investigations enabled (and described in Appendix A) include:

  Behavior of matter in extreme conditions **Shock acceleration in supernova remnants**

  Evolution of radio galaxies **Galactic distribution of diffuse ionized hydrogen**

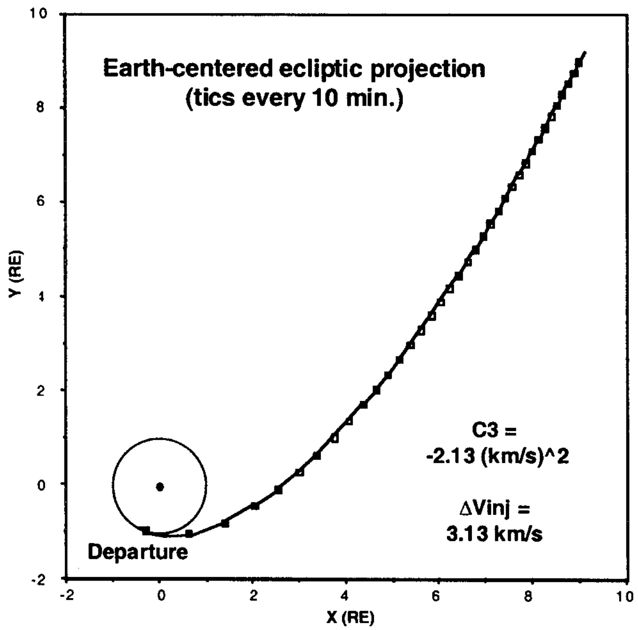
  Plasma turbulence in the galaxy **Solar transient phenomena**

- During each full Moon (as seen from Earth), the spacecraft array collects and stores its primary radio astronomy data over ≈ 1/3 orbit while the array is simultaneously shielded from both the Sun and Earth (while the normal vector to the array sweeps through ≈ 120° of the sky).
  - **This process repeats for a year at ≈ 30-day intervals with each new data set covering an angle in the sky that is stepped ≈ 30° from the previous set.**
- A similar data collection process also takes place during each new Moon, when the array is only shielded from Earth. In this case, the main targets of interest are solar coronal mass ejections.
- **Also between full Moons, each array spacecraft continuously monitors its received signal for evidence of any very strong events. The characteristics of each identified event are then summarized, stored, and transmitted to Earth later with the new Moon data.**
- Data are transmitted to Earth close to the time of a full Moon when ≈ 2/3 of each orbit is both in view of the Earth and Sun. In a series of consecutive orbits, the stored new Moon data set is transmitted, a full Moon data set is acquired and stored, and the full Moon data set is transmitted.

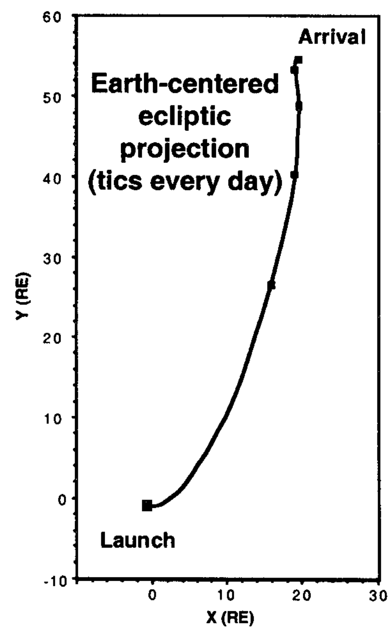
Earth-Moon Trajectory and Moon Orbit Insertion

Trajectory Plots

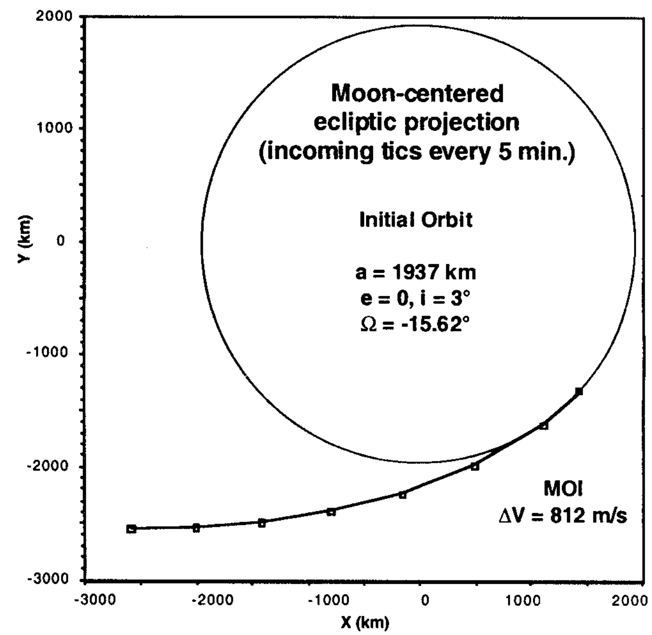
From Parking Orbit to Injection + 6 hr



Trans-Lunar Trajectory



MOI Phase Trajectory from MOI - 30 min.*



* For simplicity, the carrier is shown here as immediately going into a 200-km circular orbit. The expectation is that the first orbit would have a much higher apoapsis and that subsequent burns would lower that to 200 km. Total ΔV for this phase would still be 812 m/s.

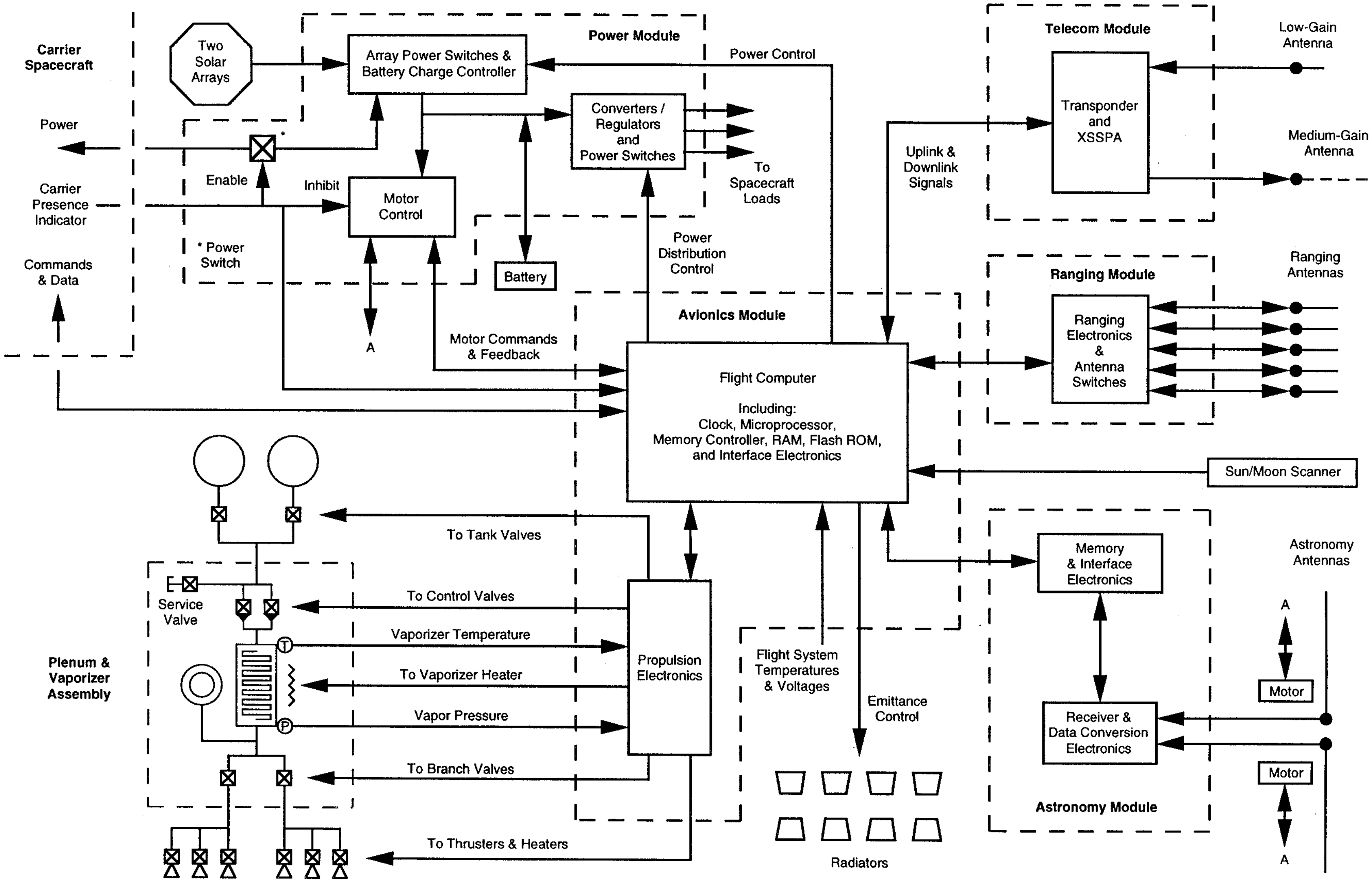
Trajectory and Array Orbits

- Launch uses a Taurus/STAR 37FM. (C_3 = -2.13 km^2/s^2, Declination = 10.7°)
- Using 812 m/s, a carrier spacecraft with 4 microspacecraft injects into a 200-km, 3° lunar orbit.
- 2 microspacecraft are deployed, and they separate from each other by 200 km along the orbit.
  - **To do this, in effect, one slows 2.2 m/s and 2 orbits later speeds up by the same amount, and the other speeds up 2.2 m/s and 2 orbits later slows by the same amount.**
- Using 166 m/s, the carrier changes its orbital plane by 6° such that it is in a 3° orbit but with the ascending and descending nodes reversed from the the initial orbit.
- The carrier deploys the remaining 2 microspacecraft, and they separate from each other by 100 km along the orbit.
  - **To do this, in effect, one slows 2.2 m/s and 1 orbit later speeds up by the same amount, and the other speeds up 2.2 m/s and 1 orbit later slows by the same amount.**
- Using 83 m/s, the carrier changes its orbital plane by 3° such that it is in a 0° orbit.
- Finally, using 166 m/s, the carrier changes its orbital plane by 6° such that it is in a 6° orbit but with the ascending and descending nodes shifted 90° from the other orbits.
  - **Further analysis (prior to this mission) may show excessive orbit maintenance is required at 6°, and a lower value (possibly 3°) could be selected instead.**

Flight System Description

- At launch, four microspacecraft form a band around the middle of a carrier spacecraft (which, although much more massive than the microspacecraft, is quite small for its propellant load).
  - **All propellant required for trans-lunar TCMs, Moon orbit insertion, and plane changes resides in the carrier, and its main engines carry out those ΔV maneuvers. (The carrier deploys two microspacecraft in one orbit plane and two microspacecraft in another plane.)**
- All spacecraft have 40-cm (wall-to-wall) octagonal cross sections, and deployed antennas extend the diameter to 10.4 m. The microspacecraft shells are 49 cm long, and the carrier shell is 133 cm.
- Except that the carrier has extensive block redundancy while the microspacecraft are each essentially single string, much of the same equipment design is used in both.
  - **Astronomy, Power, Ranging, and Telecom Modules are the same as are the flight computers, astronomy antennas, ranging antennas, +Z-axis antennas, battery cells, and solar cells. Propulsion and temperature control subsystems, however, are different.**
    - **The carrier uses a hydrazine propulsion subsystem and employs a loop heatpipe in its temperature control. The microspacecraft use vaporizing liquid ammonia propulsion subsystems and employ controlled emittance radiators.**
- The microspacecraft use spin stabilization, and the carrier is 3-axis stabilized but rolls at 1 RPM.
- Astronomy investigations are in the 30 kHz–30 MHz range, communications with Earth use X-band, and spacecraft–spacecraft ranging uses UHF.

Radio Astronomy with Microspacecraft
Microspacecraft Block Diagram

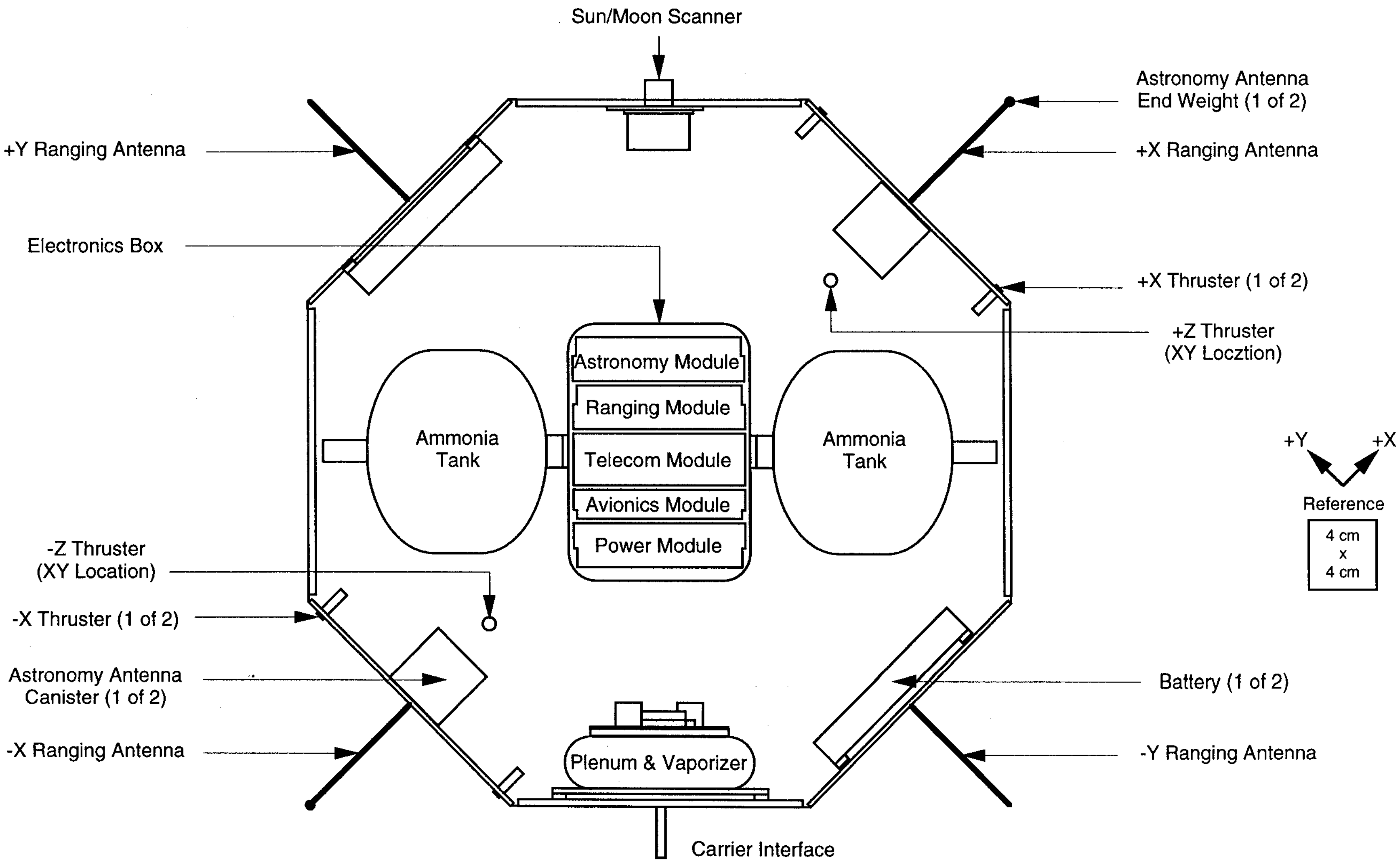


Microspacecraft Configuration

- Core
  - A 12-cm high, octagonal structure with 40 cm between side faces forms the core of the spacecraft and contains the batteries, electronics, Sun/Moon scanner, stowed radio astronomy antennas, and propulsion subsystem.
  - Attachment to the carrier is through one side face of the core.
- Shell
  - An octagonal (quasi-cylindrical) shell extends both upward and downward from the center plane of the core by 24.5 cm (for a total length of 49 cm), and its exterior is covered by solar cells except for a 2-cm band that is centered on the center plane.
- Antennas
  - A very narrow mast extends upward from the top of the core and supports the receiving and transmitting telecommunication antennas and a +Z ranging antenna above the top of the shell. The top of the highest antenna is 57 cm above the center plane.
  - Four additional 8-cm ranging antennas extend outward from the ±X and ±Y faces of the core. The antennas are hollow and have interior surface insulation.
  - Radio astronomy wire antennas mechanically feed through the ±X ranging antennas and, after deployment, extend outward ≈ 5 m each.

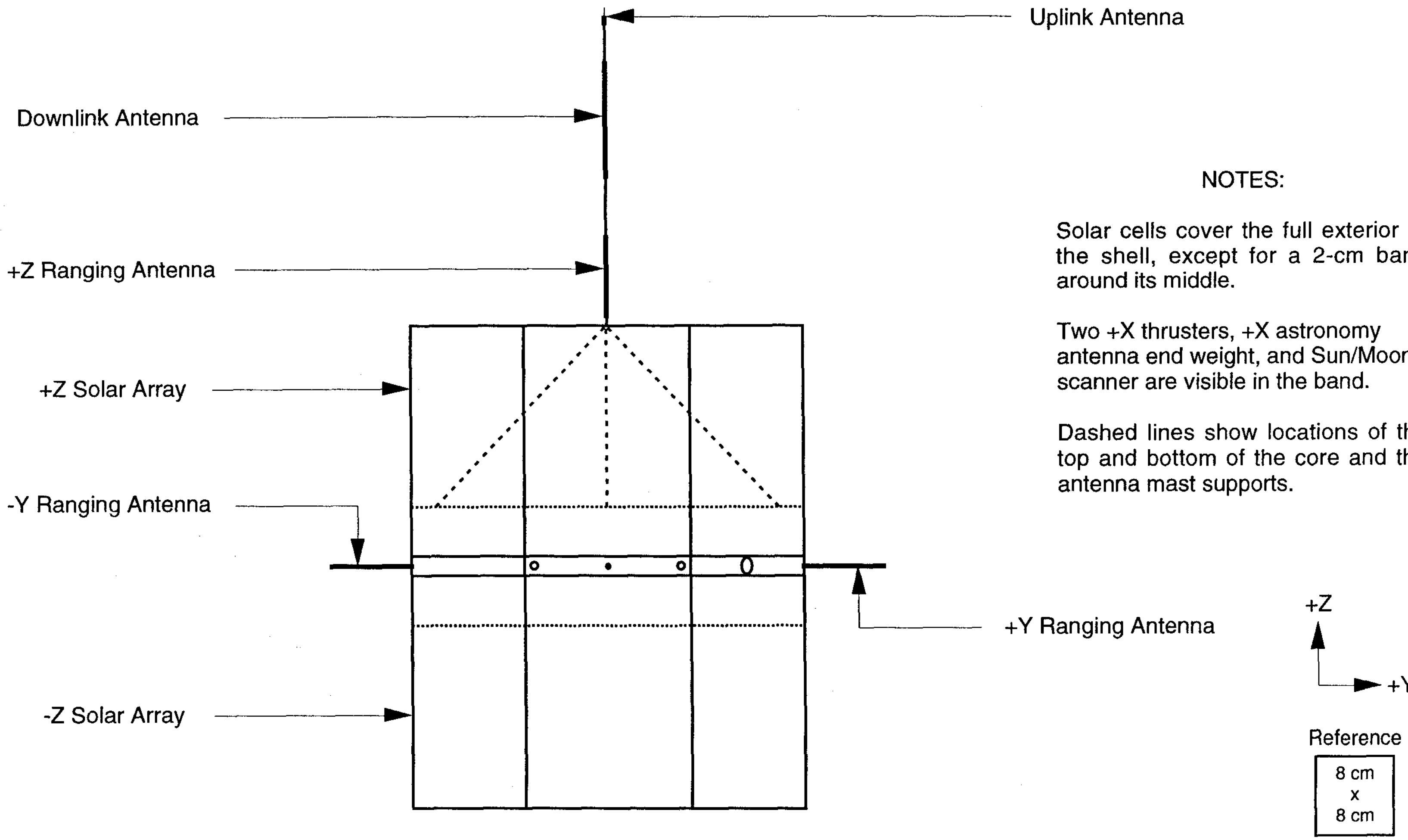
Microspacecraft Configuration

Simplified View of Core XY Cross Section with Astronomy Antennas Stowed
(Internal Structure Is Not Shown)



Microspacecraft Configuration

Side View



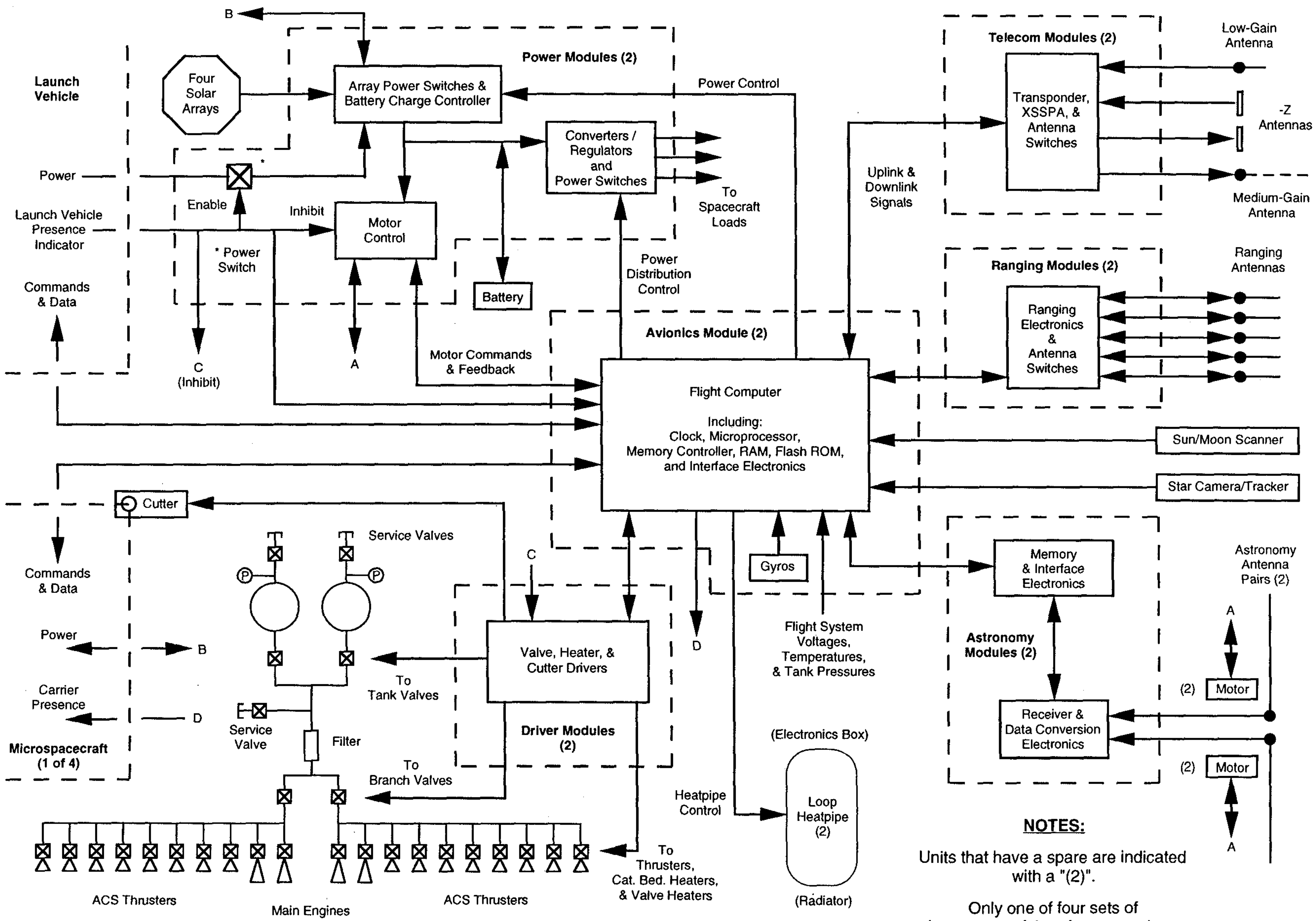
NOTES:

Solar cells cover the full exterior of the shell, except for a 2-cm band around its middle.

Two +X thrusters, +X astronomy antenna end weight, and Sun/Moon scanner are visible in the band.

Dashed lines show locations of the top and bottom of the core and the antenna mast supports.

Radio Astronomy with Microspacecraft
Carrier Block Diagram



NOTES:

Units that have a spare are indicated with a "(2)".

Only one of four sets of microspacecraft interfaces are shown.

Carrier Configuration

- Core
  - **An octagonal structure* forms the core of the spacecraft and contains high-capacity batteries, two sets of electronics, two sets of stowed radio astronomy antennas, and microspacecraft deployment hardware (next to four sides).**
- Shell
  - **An octagonal shell with closed ends extends both upward and downward from the center plane of the core by 66.5 cm (for a total length of 133 cm), and its radial exterior is covered by solar cells except for a 14-cm band that is centered on the center plane and 3-cm bands at the top and bottom ends.**
- Tanks, Main Engines, Primary Telecommunication Antennas, and Alternate Ranging Antenna
  - **Enclosed by the shell is a pair of propellant tanks with one above and one below the core. The outlet for each tank is at its +Z end.**
  - **A narrow mast surrounded by four, +Z-facing main engines extends upward from the shell +Z surface and supports telecom antennas and a +Z ranging antenna above the shell. Engines at the ±X sides are in propulsion Branch 1; engines at the ±Y sides are in Branch 2.**
    - **Due to proximity to the main engines, these antennas are designed to survive high temperature. The top of the highest antenna is 105 cm above the center plane.**

* Like the microspacecraft core, the carrier core is 12-cm high and 40-cm between side walls.

Carrier Configuration

- Other Antennas, Attitude Control Thrusters, Celestial Sensors, and Launch Interface
  - **Hollow, insulated, ranging antennas* extend outward from the ±X and ±Y core faces. After deployment, radio astronomy antennas* extend through one pair of faces. (The other pair of antennas, which operates with the spare Astronomy Module, can also be deployed.)**
  - **Eight attitude control thrusters are located in the upper 3-cm band and eight more are located in the lower 3-cm band. Locations and thrust directions are as follows:**

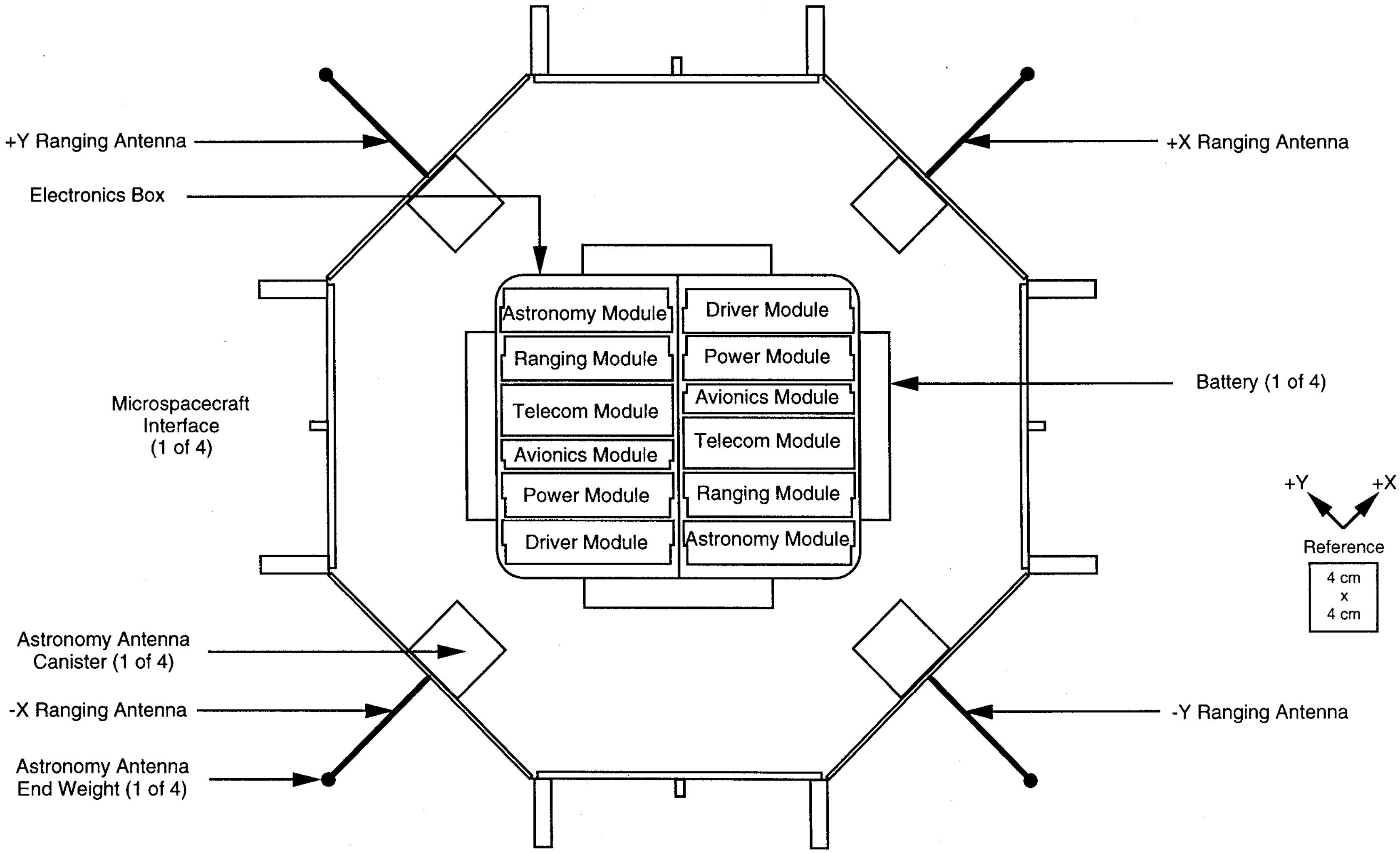
Branch	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
Band	+Z	+Z	+Z	+Z	-Z	-Z	-Z	-Z	+Z	+Z	+Z	+Z	-Z	-Z	-Z	-Z
Side	+X	+Y	-X	-Y	+X	+Y	-X	-Y	+X	+Y	-X	-Y	+X	+Y	-X	-Y
Thrust	+Y	-X	-Y	+X	-Y	+X	+Y	-X	-Y	+X	+Y	-X	+Y	-X	-Y	+X

  - **A star camera/tracker looks downward from the shell bottom surface and extends downward to 78.5 cm below the center plane.**
  - **A Sun/Moon scanner looks radially outward from the +X face in the 3-cm band at the bottom (-Z end) of the shell.**
  - **The carrier side of a ring used for separation of the carrier from the STAR 37FM stage is connected to the bottom of the shell.**
  - **Alternate telecom antennas face in the -Z direction from the ±Y sides of the ring.**

* Dimensions of these items are the same as those in the microspacecraft.

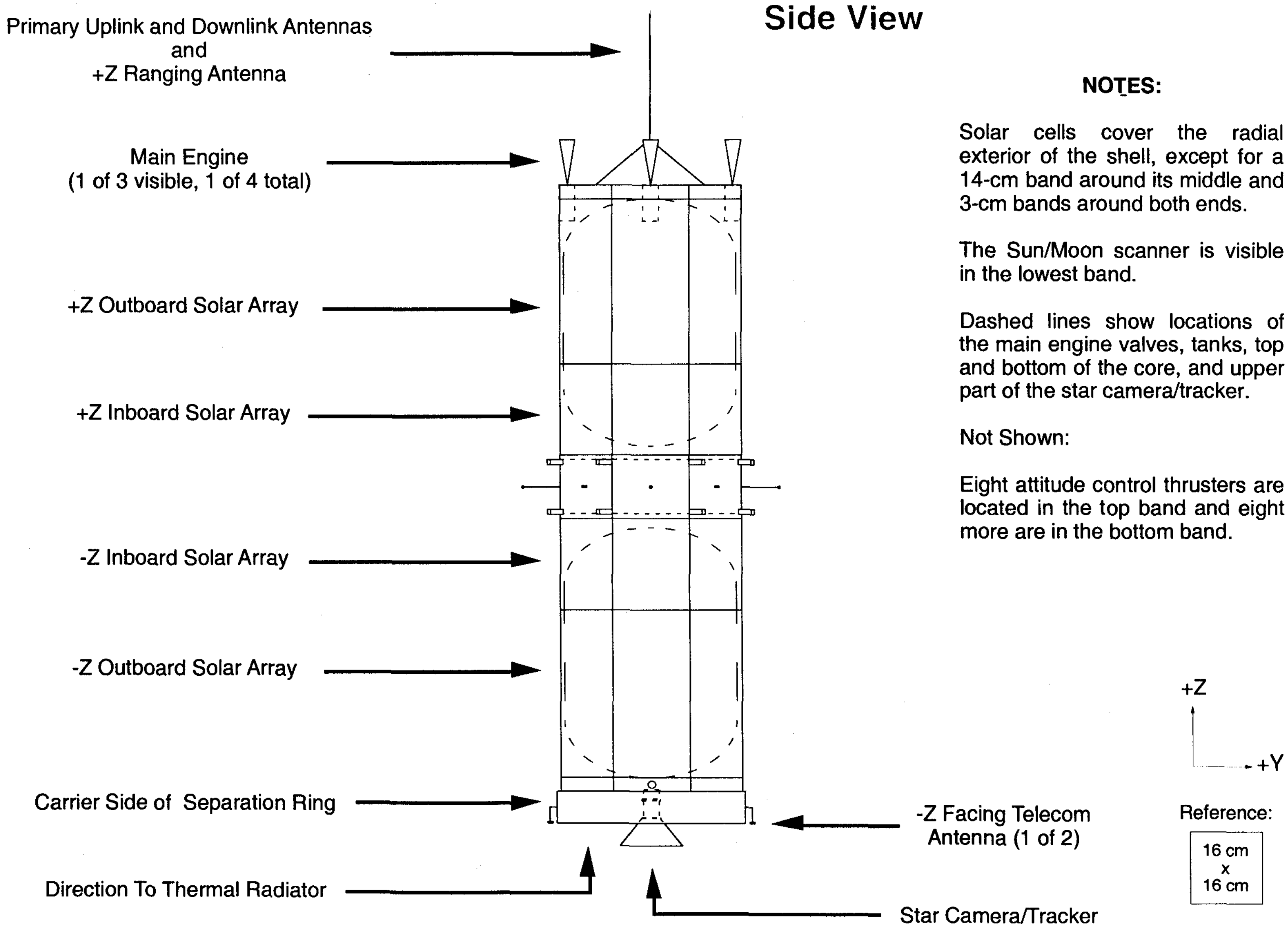
Carrier Configuration

Simplified View of Core with Astronomy Antennas Stowed
(Internal Support Structure and Separation Devices Are Not Shown)



Radio Astronomy with Microspacecraft
Carrier Configuration

Side View



NOTES:

Solar cells cover the radial exterior of the shell, except for a 14-cm band around its middle and 3-cm bands around both ends.

The Sun/Moon scanner is visible in the lowest band.

Dashed lines show locations of the main engine valves, tanks, top and bottom of the core, and upper part of the star camera/tracker.

Not Shown:

Eight attitude control thrusters are located in the top band and eight more are in the bottom band.

Average Power Summaries

Available Power from Illuminated Solar Arrays
(Rough Approximations in Watts)

	Injection from Earth	Cruise	Moon Orbit Insertion	First Plane Change	Final Orbit	Final Orbit
	Attached System	Attached System	Attached System	Attached System	Carrier Alone	Micro S/C Alone
+Z Outboard Array	27	40	40	40	40	N/A
±Z Inboard Arrays	OFF	OFF	OFF	OFF	43	N/A
-Z Outboard Array	OFF	40	40	40	40	N/A
Micro S/C Arrays	88	128	128	77	N/A	53
TOTAL	115	208	208	157	123	53
TOTAL Available To Carrier*	97	190	190	148	123	N/A

* Each attached microspacecraft uses 4.5 W (in its flight computer, Sun/Moon scanner, and power electronics).

Average Power Summaries

Rough Power Estimates

	Microspacecraft Transmit Mode (W) [≈ 2/3 orbit, in light]	Microspacecraft Primary Research Mode (W) [≈ 1/3 orbit, in dark]	Carrier Transmit Mode (W) [≈ 2/3 orbit, in light]	Carrier Primary Research Mode (W) [≈ 1/3 orbit, in dark]
Astronomy Module	1.0	2.0	1.0	2.0
Ranging Module	0.0	5.0	0.0	5.0
Attitude References	0.1	0.1	1.5	1.5
Flight Computer	3.9	3.9	3.9	3.9
Transponder	5.0	3.0	5.0	3.0
RF Power Amplifier	15.2	0.0	15.2	0.0
Thrusters and Associated Heaters	0.0	1.5	16.0	18.0
TOTAL USER LOADS	**25.2**	**15.5**	**42.6**	**33.4**
Conversion, Regulation, and Switching	3.0	1.9	5.1	4.0
Core/Tank Heaters and Other Temperature Control	0.0	0.0	0.1	4.5
TOTAL REQUIRED	**28.2**	**17.4**	**47.8**	**41.9**
Battery "Load"	14.5	-23.4	42.7	-68.9
TOTAL WITH BATTERY	**42.7**	**-6**	**90.5**	**-27**
Margin	10.3	6	32.5	27
ARRAY POWER	**53**	**0**	**123**	**0**

Mass Summaries

- Each microspacecraft has a 0.9 kg propellant load. Of that, ≈ 0.08 kg is for 4.4 m/s that initially moves the microspacecraft to its nominal east-west position in the array, ≈ 0.66 kg is for an allocation of 40 m/s for orbit maintenance, and ≈ 0.16 kg is available for attitude control and spare.
  - **Propellant ΔV mass is based on Isp = 92.8 lbf-s/lbm and 90% ΔV efficiency (while spinning).**
- The carrier has an 80 kg propellant load; its use is itemized on Page 28.
  - **Propellant ΔV mass is based on main engine Isp = 223.8 lbf-s/lbm, which has been reduced from 228 lbf-s/lbm to account for propellant that is used for attitude control during ΔV burns. (Propellant for all other attitude control purposes is also included in the numbers listed.)**
- A buildup of the complete system mass from the individual rough mass estimates is as follows:

56 kg estimate for 4 microspacecraft with 35% margin and propellant (see Page 27)*
128 kg estimate for the carrier with 35% margin and propellant (see Page 27)*
10 kg allocation for STAR 37FM interconnection and separation hardware
10 kg allocation for STAR 37FM supplemental stabilization and despinning hardware
----
204 kg Subtotal
102 kg for an additional margin of 50%
----
306 kg Launch Vehicle Capability

* ΔV propellant use calculations are conservative in that they were made after addition of the 35% margin.

Mass Summaries

Rough Mass Estimates

	Microspacecraft Mass (kg)	Carrier Mass (kg)
Astronomy Antennas and Module	0.9	1.8
Ranging Antennas and Module	0.7	1.2
Batteries	0.6	1.1
Power, Driving, and Deployment Electronics	0.4	1.5
Guidance, Control, & Computation	0.2	0.5
Telecommunications	1.3	2.7
Temperature Control	0.5	1.8
Propulsion (dry)	0.4	8.5
Shell / Solar Array	1.8	6.4
Non-Shell Structure, Packaging, Devices, and Cabling	2.9	9.7
SUBTOTAL (dry)	**9.7**	**35.2**
Margin (35%)	3.4	12.4
TOTAL (dry)	**13.1**	**47.6**
Propellant	0.9	80.0
TOTAL (wet)	**14.0**	**127.6**

Radio Astronomy with Microspacecraft
Carrier ΔV and Propellant Summaries

Velocity Change	Initial (Injected) Mass	Propellant Used**
	183.6 kg	
95 m/s* + 812 m/s (TCMs + Orbit Insertion)		62.3 kg
	121.3 kg	
	Deploy 2 Microspacecraft	
	93.3 kg	
166.5 m/s (6° Plane Change)		6.8 kg
	86.5 kg	
	Deploy 2 Microspacecraft	
	58.5 kg	
83.3 m/s + 166.5 m/s (3° & 6° Plane Changes)		6.3 kg
	52.2 kg	
75 m/s (Orbit Maintenance Allocation)		3.4 kg
	48.8 kg Final (EOM) Mass with 1.2 kg residual propellant	

* Based on first TCM at 12 hours after injection

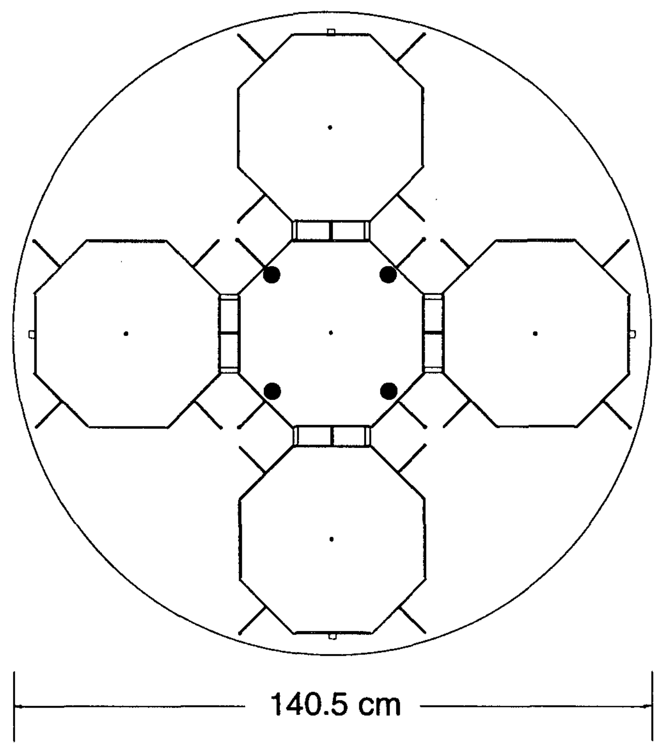
** Includes both ΔV and attitude control propellant

Tracking and Navigation

- Data from the entire array of five spacecraft can be acquired simultaneously using different X-Band transmission frequencies and a single 34-m Deep Space Network station.
  - **The station points to the approximate center of the array and makes a wide-band recording of the received signals. (Up to a 0.9 dB pointing loss is expected and accounted for in link calculations.) Individual transmissions are subsequently extracted from the recording.**
  - **Doppler navigation data on all spacecraft can also be extracted from the recording. Two-way data is available from one spacecraft, and one-way data is available from the others.**
- Two consecutive, 9-hour, 34-m station passes at the approximate time of each full Moon are sufficient to return all science and engineering data when the rate is limited to ≈ 117 kb/s, and one, 9-hour, 34-m station pass is needed when the highest data rate of ≈ 260 kb/s is available.
  - **Some additional tracks could be needed in support of navigation and commanding for orbit maintenance maneuvers. However, if another mission (such as SELENE) has previously mapped the far-side gravity field of the Moon, it should greatly simplify orbit analysis.**
- Spacecraft-to-spacecraft navigation is also required in establishing the spacecraft array, maintaining its dynamic configuration, and analyzing the radio science data gathered by the array. (See Appendices B and C for more information.)
  - **A four-tone UHF ranging subsystem with RF-carrier phase analysis capability is included on each spacecraft for this purpose with a spare unit also available in the carrier spacecraft.**

Launch Configuration in Dynamic Envelope

Top View in Taurus / STAR 37FM with 63" Fairing



Notes:

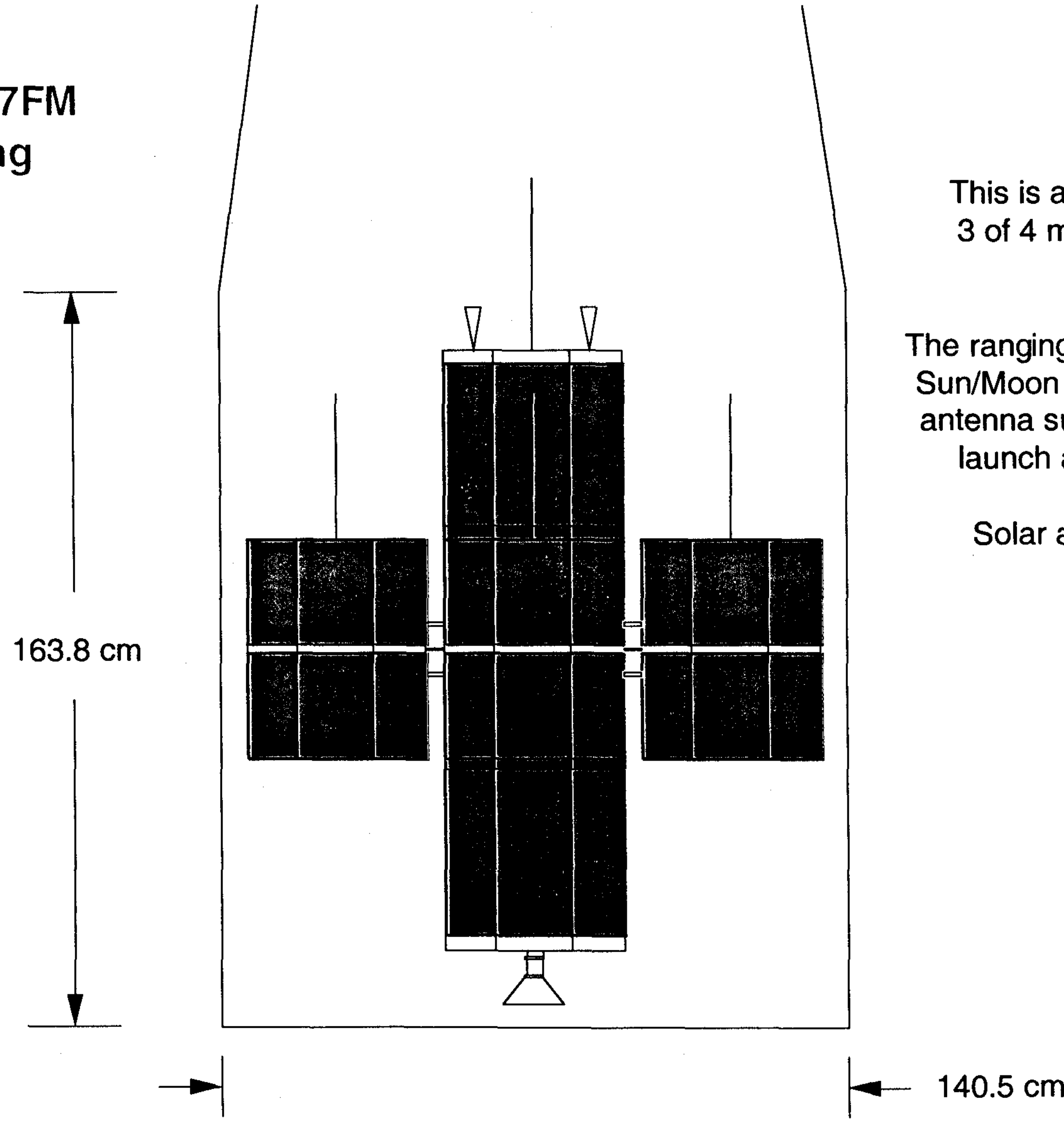
This is a simplified drawing with all microspacecraft and the carrier visible.

The ACS thrusters, carrier Sun/Moon scanner, and communication antenna supports are not shown.

Radio Astronomy with Microspacecraft

Launch Configuration in Dynamic Envelope

Side View in Taurus / STAR 37FM with 63" Fairing



Notes:

This is a simplified drawing with 3 of 4 microspacecraft and the carrier visible.

The ranging antennas, ACS thrusters, Sun/Moon scanners, communication antenna supports, -Z antennas, and launch adapter are not shown.

Solar array areas are shown as blue.

Subsystem Descriptions

Power

- The microspacecraft and carrier are normally oriented with their spin axes (i.e., center lines) perpendicular to the ecliptic plane so the Sun illuminates the sides of their solar arrays.
  - **Triple-junction GaAs solar cells are used in the arrays, and available power is ≈ 53 W for each microspacecraft and ≈ 123 W for the carrier. The cells have a grounded ITO coating.**
  - **While attached to the microspacecraft, the carrier does not use its inboard solar arrays but does have access to power from the microspacecraft solar arrays.**
- Rechargeable batteries store energy for use during launch and occultations and, as needed, use during ΔV maneuvers. (Full solar power is available in the lunar orbit insertion orientation.)
  - **Solar array switching and pulse-width modulation techniques prevent overcharging.**
  - **Storage capabilities are ≈ 60 Wh for each microspacecraft and ≈ 120 Wh for the carrier.**
- Power converters/regulators convert power from the battery bus to needed voltages.
- MOSFET power switches and valve-driver circuits control power distribution.
- Power electronics are located in the Power Module in the Electronics Box, and the carrier includes a spare Power Module.
  - **Also included in the case of the carrier is a pair of Driver Modules. These have high-power, valve-driver circuits, and they also control power for releasing the microspacecraft.**

Information Processing and Control

- During a typical science data gathering pass behind the far side of the Moon, data is acquired by each spacecraft at ≈ 1 Mb/s for ≈1/3 orbit and stored along with needed data from the avionics in its Astronomy Module.
  - **Data from the avionics includes time, calculated radio astronomy antenna clock angle and rate, calculated ranges to the other spacecraft, and engineering housekeeping data.**
  - **Total storage capability is 384 MByte.**
- During science data return, when the Earth is not blocked by the Moon, the stored data along with real-time engineering housekeeping data is sent to Earth at a rate that depends on Earth range and declination of Earth with respect to the transmitting antenna.
  - **Approximately 75–166 MByte can be returned by a spacecraft to Earth during the unblocked portion of each orbit (i.e., ≈2/3 orbit).**
- Flight system engineering information processing and control functions are carried out by a microprocessor (PPC 603e or better) in the Avionics Module (with two modules in the carrier).
  - **A 16 MByte flash ROM provides non-volatile storage, a 64 MByte RAM with EDAC provides working memory, and a memory controller coordinates memory activities.**
  - **An FPGA provides digital input/output interfacing and uses negotiated interface standards.**
  - **An analog multiplexer and ADC are used in monitoring engineering transducers, etc.**

Telecommunications

- Telecommunications are X-Band and include a transponder and RF power amplifier in the Telecom Module, a single 3 cm x 10 cm x 10 cm package. (This volume does not include DC-DC power converters, which are located in the Power Module, or any Ka-band electronics.)
  - **The transponder provides receiver, exciter/modulator, and navigation functions, and a solid-state RF power amplifier boosts the transmitter output signal to 6 W_{RF}.**
- Both low-gain and medium-gain antennas are located on the Z axis at the +Z end of the spacecraft and have toroidal patterns at 90° from the Z axis.
  - **At the top is a choked-monopole antenna that is used for the uplink. It has a 2.15 dBi gain and 68° beamwidth (i.e., -3 dB points at 56° and 124° cone angles from the +Z axis).**
  - **Just below it is a collinear array of four dipole elements that form the downlink antenna. It has a 7 dBi gain and 14° beamwidth (with -3 dB cone angles of 83° and 97°).**
- In lunar orbit, with the Z axis perpendicular to the ecliptic, the cone angle to the Earth varies from 85° to 95°, so, even with a 2° pointing error, the Earth stays within both antenna patterns. Microspacecraft downlink performance to a 34-m station varies from ≈ 117 kb/s to ≈ 260 kb/s.
  - **Carrier downlink performance is slightly less due to switch losses and longer RF cables.**
- The carrier includes the same Telecom Module and antennas, a spare Telecom Module, two -Z-facing 5 dBi patch antennas (for uplink and downlink when Earth is relatively near the -Z axis during the lunar orbit insertion), and RF switches to change modules and antennas.

Microspacecraft Guidance and Control

- Each microspacecraft is slowly spinning at the time of its release from the carrier with its spin axis (the Z axis) perpendicular to the ecliptic plane. It maintains this orientation and all-spin stabilization throughout its subsequent existence.
  - **The carrier temporarily increases its turn rate to 18°/s (3 RPM), deploys two microspacecraft from opposite sides at one time, and returns to a 1 RPM turn rate. (Carrier thrusters are momentarily disabled during the deployments.)**
- Microspacecraft orientation is determined using a radially pointed Sun/Moon scanner that has a field of view that is very narrow in the clock direction but 78° in a plane that includes the microspacecraft Z axis. (Much of the sky is swept out during a turn.)
  - **The scanner uses a 1200-pixel line array of 12 μm x 12 μm pixels and optics with 0.89-cm focal length and 4.45 F number.**
  - **The Sun and partially–to–fully illuminated face of the Moon can be seen through most of each orbit around the Moon and are used to determine orientation and spin rate and phase.**
- After the microspacecraft have completed all the ΔV maneuvers needed to establish the desired separation distance, the pair of radio astronomy wire antennas is slowly deployed while the controlled spin rate is gradually decreased to 1 RPM.
  - **Each antenna is deployed by a mechanism with a small, momentum-compensated, reversible motor. Outward pressure from the mechanism and centrifugal force on the antenna (and a very small weight at its end) combine to simplify the deployment process.**

Carrier Guidance and Control

- After injection on its trajectory to the Moon, yo-yos despin the carrier to 1 RPM, and it initiates 3-axis attitude control and actively maintains the turn. This stabilization mode and controlled roll turn are maintained throughout the mission, except during Z-axis reorientations.
  - **The carrier normally maintains its roll axis (the Z axis) perpendicular to the ecliptic plane, except when it needs to point its main engines (and that axis) for ΔV maneuvers.**
  - **Except during ΔV maneuvers, the carrier normally maintains its roll rate within ± 10% and uses ± 1° deadbands for both pitch and yaw.**
- An axially pointed, 60° x 60° star camera/tracker provides 3-axis attitude determination. The camera/tracker has an 856 x 856 array of 12 μm x 12 μm pixels and optics with 0.89-cm focal length and 2.83 F number.
  - **A Sun/Moon scanner (which can also use the Earth in early cruise) provides 3-axis backup data during most of cruise and most of each orbit around the Moon .**
  - **A 3-axis microgyro is the inertial reference and provides the primary orientation data during the launch phase. It also provides supplemental data during maneuvers and when the Moon blocks the Sun. Two of these gyros are available in the carrier.**
- After all microspacecraft have been deployed and all planned maneuvers have been completed, the carrier slowly deploys an astronomy antenna pair while maintaining its 1 RPM controlled roll. (A second antenna pair can also be deployed that operates with the spare Astronomy Module.)

Microspacecraft Propulsion

- Liquid ammonia propellant is used and is stored in 2 composite-overwrapped tanks.
  - **The tanks are oblate spheroids with eccentricity = 0.75. Tank inside dimensions are: total length = 10.5 cm, cylindrical length = 2.71 cm, and radius = 5.9 cm.**
  - **A 0.9-kg ammonia load fills 88% of the 1.77-liter combined pressurized tank volumes, and, primarily to prevent cavitation during launch, a helium load at ≈724 mm of Hg partial pressure fills the remaining volume. Screens at the tank outlets prevent helium escape, and valves at the tank outlets provide control of propellant transfer (and mass shifting).**
- When thrust is needed, a control valve is used to meter liquid propellant into an electrically heated vaporizer, and a 178 cm^3 toroidal plenum buffers vapor use by the thrusters.
  - **Vapor pressure is held down near ≈1430 mm of Hg to prevent re-liquefaction above -20 °C.**
- Six very small 5-mN thrusters are arranged in couples and provide spin-rate and spin-axis-orientation control as well as ΔV capability in lateral and axial directions.
  - **90% efficient lateral ΔVs can be conducted using alternating pairs of lateral thrusters with each pair firing for ≈90° out of 360°.**
  - **This set of thrusters in combination with 2 branch valves, redundant control valves, and the tank valves can handle any valve failure with only graceful degradation.**

Carrier Propulsion

- Hydrazine propellant is used and is stored in 2 aluminum-lined, composite-overwrapped tanks.
  - **The dimensions of each tank are: length = 54.6 cm, cylindrical length = 29.5 cm, and radius = 19 cm, and the combined tank volumes hold an 80-kg hydrazine load along with sponge-type propellant management devices, pressurizing gas, and outlet screens.**
  - **Liquid outlets are at the +Z ends of the tanks, since acceleration from the main engines forces propellant in that direction. (When those engines are not firing, the PMDs are able to counteract rotation and attitude control accelerations and still get propellant to the outlets.)**
  - **Latch valves at the outlets allow control of propellant use (and center-of-mass shifting).**
- Four 8-lbf ($\approx$36-N) main engines support large ΔV maneuvers, and 16 low-minimum-impulse, 0.2-lbf ($\approx$0.9-N) thrusters provide attitude control and also allow small lateral ΔV maneuvers.
  - **When in use, the main engines take over pitch and yaw control (through off-pulsing).**
  - **Two latch valves control separate propulsion branches with two main engines and eight thrusters in each branch. (The thrusters in one branch are spares and are normally kept dry.)**
  - **Attitude control uses thruster couples to prevent undesired ΔV, and the thruster locations and orientations provide some functional redundancy beyond the full block redundancy.**
- Other propulsion components include three low-mass service valves, a propellant filter, and two low-mass pressure transducers.

Structure

- Each aluminum Electronics Box provides a central spacecraft structural element and packages the electronics modules, helps isothermalize them, and helps shield them from radiation.
- Extending radially outward from each Electronics Box and connecting each of its four side walls with a core face is a 4-wall structure composed of aluminum and G10 fiberglass elements.
  - **In the microspacecraft, the top and bottom walls of these structures are aluminum and also provide the thermal radiators for the spacecraft. The structure is strengthened on the side of the microspacecraft that interfaces with the carrier.**
  - **In the carrier spacecraft, all of these structures are strengthened.**
- Each microspacecraft-carrier mechanical interface includes a tension bolt that pulls the two spacecraft together against 4-cm supports at the four corners of a carrier core face.
  - **The tension bolts in each spacecraft are held by a ring that is supported from four corners of its Electronics Box. The corner supports from the carrier face are made of an RF-transparent material to prevent interference with the carrier ranging antenna patterns.**
  - **Each tension bolt (and an electrical interface cable) feeds through a single cutter with dual initiators on the carrier, and a spring helps separate the spacecraft after actuation. (Cutter actuation may present a significant mechanical shock to the spacecraft cores.)**
- Composite shells are fastened to the cores and act as the substrates for the solar arrays. The carrier shell is also fastened to 16 G10 webs that connect to bosses at the ends of the tanks.

Temperature Control

- Since the spacecraft rotate about their Z axes, and normally have those axes perpendicular to the Sun direction, it helps limit maximum shell temperatures and isothermalize their interiors.
  - **With this normal Z-axis orientation, it also provides sun-free surfaces at the top and bottom of the microspacecraft cores and of the carrier ± Z-facing surfaces.**
- Radiators on the top and bottom of the microspacecraft cores and on the -Z-facing surface at the bottom of the carrier radiate away excess heat from the electronics boxes.
  - **Heat radiation control is provided by controlled-emittance surfaces on the microspacecraft radiators and by a loop heatpipe (and spare) on the carrier, linking its core to its radiator.**
- Unwanted conductive heat transfer between the electronics boxes and shells (and between the tanks and shells) is minimized by using G10 fiberglass as part of the structure between them.
- Unwanted radiative heat transfer in the spacecraft is minimized using 10-layer thermal blankets.
  - **This insulation is confined to the cores of the microspacecraft but covers nearly all the inner surface of the carrier shell. (Within blanketed areas, however, heat transfer is generally desired, and black paint is used to reduce temperature differences.)**
- Heaters are used to prevent excessive cooling when the Moon blocks the Sun.
  - **Their primary use for this purpose is for the microspacecraft thrusters and those wet-branch carrier thrusters/engines that do not have their catalyst beds heated at that time.**

Conclusions
and
Recommendations

High-Level Conclusions

- Valuable radio astronomy investigations with microspacecraft are feasible.
- The basic mission concept developed in this study, independent of its implementation with microspacecraft, appears feasible.
  - Probably the most important uncertainty is the adequacy of the orbit maintenance ΔV allocations (and the amount of tracking and human effort required for adequate maintenance of spacecraft positions within the array).
    - **These analyses would involve uncertainties in the lunar gravity field and maneuver accuracies and were well beyond the scope of this study.**
- Implementation of this mission using microspacecraft concepts developed in this study appears feasible, would greatly reduce required launch capability, and could significantly reduce the recurring cost of the spacecraft in the array.
  - These concepts are dependent on certain technology developments, and, of these, probably the most challenging is development of the X-band transponder and associated RF power amplifier.

Recommendations

- It is recommended that the X-band transponder and associated RF power amplifier discussed in this report be developed. It is a very important development needed not only for this mission implementation but also for many other potential microspacecraft missions.
  - **It is a full-function transponder/amplifier with filtering on the RF input, clean 6 W_{RF} output, and Deep Space Network compatibility. Other basic characteristics include:**

    Size $\leq$ 3 cm X 10 cm X 10 cm; Mass $\leq$ 0.9 kg;
    DC Power Required $\leq$ 3.0 W (receive), $\leq$ 20.2 W (receive plus transmit).
    Note: Built-in DC-DC power converters and Ka-band functions are not required.
  - **Key developments probably include a mixed-signal ASIC as well as RF MMICs for the front end, first local oscillator synthesizer, and downlink synthesizer.**
- It is recommended that the microspacecraft thrusters discussed in this study be fully developed.
  - **These are also important for many other microspacecraft missions as well as this one, and limited development is underway. Characteristics of these cold gas/vapor thrusters include:**

    Size $\leq$ 1 cc; Mass $\leq$ 8 g; Power $\leq$ 0.5 W at 5 V_{DC}; Thrust $\approx$ 5 mN;
    Min. Impulse $\leq$ 0.15 mN-s; Specific Impulse (at 0 °C with ammonia vapor) $\geq$ 93 lbf-s/lbm.
- For the carrier spacecraft implementation in this mission, as well as other very small spacecraft, existing development efforts for 160 g, 0.9 N, 1 mN-s hydrazine thrusters and 3-axis microgyros need to be brought to successful conclusions.

Appendices

Introduction [1]

An interferometer array in space providing high dynamic range images with arcminute angular resolution at several MHz could allow a wide range of problems in solar, planetary, galactic, and extragalactic astrophysics to be attacked. In addition, it is likely that completely unexpected objects and processes would be discovered by such an instrument, as has often happened when high resolution astronomical observations first become possible in a wide, new region of the electromagnetic spectrum. The public funds astronomy primarily to enable discovery, and the mission described here could have a very high potential for discovery.

From the interstellar plasma absorption cut-off near 30 kHz (10 km wavelength) to the ultraviolet gap at about 3 x 10E15 Hz (100 nm wavelength), the electromagnetic spectrum spans 11 orders of magnitude in frequency. The lower quarter of that span is largely unexplored. Below 30 MHz very strong terrestrial radio interference and ionospheric absorption and refraction make the reception of cosmic radio waves extremely difficult. Below 10 MHz the ionosphere becomes opaque almost all the time over almost all the earth. Even at the best ground-based locations, astronomical observations are impossible below about 3 MHz. Between 30 kHz and 3 MHz there have been some observations from individual spacecraft, but with antennas having almost no angular resolution. Harwit (1981) has studied the process of discovery in astronomy, and two of his conclusions are particularly pertinent: "Many discoveries...depended on equipment less than five years old" (i.e., new discoveries require new observing capabilities) and "About half the discoveries made have been serendipitous." Furthermore, in his study all but 4 of 43 phenomena were discovered in the eight decade range between 30 MHz and 3 x 10E15 Hz. Harwit thought a great many more phenomena in the universe are still awaiting discovery; how many of these phenomena remain to be discovered in what is arguably the last frontier in the electromagnetic spectrum, the three decades between 30 kHz and 30 MHz?

Structure and Evolution of the Universe [1]

* How does matter behave in extreme conditions?

Coherent emission processes, capable of producing extremely high brightness temperature radio emission, are most common at long wavelengths where the wavelength becomes much larger than the typical distance between radiating particles. The Sun, giant planets, and the Earth's magnetosphere all display extremely strong coherent emission at low radio frequencies, and it is likely that similar collective plasma processes produce very strong radio emission from objects such as supernova remnants, Seyfert galaxies, and quasars.

* Shock acceleration in supernova remnants

In general, observations of supernova remnants at low frequencies could test the hypothesis that these objects are the source of cosmic rays. Diffusive shock acceleration in supernova remnants has long been thought to produce the observed high energy cosmic rays. However, the spectrum of cosmic ray electrons differs from that of the ions, and this may indicate a different origin for cosmic ray electrons. Furthermore, it is difficult for thermal electrons to gain enough momentum (compared to the thermal ions) to respond to diffusive shock acceleration. Only observations at low frequencies can detect (via their synchrotron emission) the presence of the relatively low energy electrons which need to be available for injection into the diffusive shock acceleration mechanism.

Appendix A - Science (SEU continued)

* How do radio galaxies evolve?

This mission could search for "fossil" radio components associated with presently radio-quiet galaxies. Are there significant numbers of galaxies which had active nuclei in the distant past but are now quiescent? The very long radiative lifetimes of electrons at low frequencies will preserve evidence of early phases of activity in galaxies that are too faint at higher frequencies to be included in existing radio catalogs. The discovery of a significant number of "fossil" radio galaxies would provide important new constraints on galaxy evolution, particularly the accretion history of central black holes.

* Distribution of diffuse ionized hydrogen

This mission could determine the galactic distribution of diffuse ionized hydrogen by measuring free-free absorption of radiation from a large number of bright galactic and extra-galactic sources. These measurements could cover high galactic latitudes and could be combined with pulsar dispersion measures at low galactic latitudes. Ionized hydrogen is "the only major component of the interstellar medium that has not yet been surveyed" (Reynolds, 1990). It is important to determine the large-scale distribution of diffuse HII both to improve our understanding of the heating and ionization processes in the interstellar medium and to account for the emission or absorption by this gas in other parts of the spectrum.

* Plasma turbulence in the galaxy

This mission could study radio wave scattering by the interstellar medium and determine the turbulence properties of the interstellar plasma. With many measurements of the angular broadening of distant sources it would be possible to map the distribution of scattering material.

The Sun-Earth Connection [1]

The study of the nature and evolution of solar transient phenomena is essential to understanding the Sun-Earth connection. Phenomena such as solar flares, filament eruptions, fast mode shocks, and coronal mass ejections (CMEs) are manifested by distinct types of non-thermal radio bursts. The transient disturbances traveling through interplanetary space generate radio emissions at the characteristic frequencies of the plasma. The important solar-terrestrial physics goals the mission could address are:

* Tracking the transport of CMEs in the interplanetary medium to improve understanding of their evolution and propagation, to distinguish unambiguously between Earth-directed and anti-Earth-directed CMEs, and to establish a metric for their "geoeffectiveness." This will test the value of CME imaging at low frequencies for space weather forecasting by future missions.

* Enhancing understanding of particle acceleration in flares and in shocks driven by CMEs and providing new insights into the radio emission mechanisms, using images of type II and III radio bursts.

NOTE: Unlike other phenomena the mission would investigate, where the measurements would be made while the spacecraft were shielded from both the Earth and Sun, the SEU investigations would be carried out while the spacecraft were only shielded from the Earth. Also, the data recorded would not be sent back to Earth until later in the Moon's orbit when its near side was fully illuminated.

Gravity

If another mission, such as SELENE, has not already measured the far-side gravity field of the Moon, the RAM mission could be used to do so at low latitudes and provide that data for the first time.

Ranging Antenna Utilization

One pair of spacecraft range at a time using one of three antenna options. The monopole +Z ranging antenna on each spacecraft has a toroidal patern with maximum gain near the XY plane. These antennas are used while each microspacecraft is initially being positioned relative to both the other microspacecraft that will share its final orbit and the carrier. (During this period, each spacecraft stays within a few degrees of the maximums of the antenna patterns of the other two spacecraft, and ranging signals suffer little loss.)

Throughout the rest of the mission, the spacecraft use their +Z antennas as much a possible for ranging, but sometimes the communication direction is relatively close to the +Z or -Z axes, where there are nulls in the +Z antenna pattern. As can be seen in the array configurations on Page 8, this condition arises when two spacecraft in different orbit planes are ranging and the north-south separation of the spacecraft is large. The problem can be exacerbated if one or both of the spacecraft have gradually moved out of their nominal east-west position within the array and there is less east-west separation between the spacecraft.

When this has resulted in the ranging communications link becoming too weak for a pair of ranging spacecraft, they switch to their ± X and ± Y monopole antennas. These antennas also have toroidal patterns, but these patterns have null axes that are in the XY plane (90° from the Z axis) and sweep through space as the spacecraft turn. Two main options are available for their use. The simplest, and the one of choice when the communication direction is very close to the Z axes, is to use just one of these antennas (any of the four). If, however, the ranging communications direction is at a significant angle with respect to the Z axes (but still too shallow to use the +Z antennas), the antenna coverage may need to be partially despun by switching back and forth between X and Y antennas every 90° of spacecraft rotation. This can keep the clock angles of the antenna pattern nulls ≥ 45° from the clock angle of the ranging communications direction. The implementation of this used here switches through all four antennas, but, depending on the actual antenna patterns, it may be possible to only use one X and one Y antenna.

Array Configuration Error Sensitivity

As long as the spacecraft positions within the array are precisely known, with the help of the ranging subsystems, relative position errors of the individual spacecraft of 10 km or even more can be easily tolerated. Differences in orbital periods, however, are a more serious concern. This is because even very small period errors can result in position drifts that over several days or weeks can accumulate in many tens of kilometers of position errors. This implies that it is important to both keep period errors small and to provide sufficient array configuration maintenance to prevent accumulation of large position errors.

Array Initialization

The first step in array configuration initialization is to establish the desired 3°, 200-km, circular orbit for the carrier with all the microspacecraft attached to it. The carrier is tracked carefully from Earth, its orbit well determined, and corrections to its orbit made and verified. The first two microspacecraft are then deployed with their small deployment ΔVs aligned in opposite directions along the orbit. The ranging subsystems are then used to measure the actual deployment velocities so they can be factored into the orbit separation burns that follow. (Since the +Z axis ranging antennas are used in this process, there are no antenna switching transients that could complicate differential velocity determination using RF-carrier phase analysis.) Trim burns following the initial separation burns establish the first two microspacecraft positions precisely. Then the carrier spacecraft, with the remaining two microspacecraft, makes its 6° plane change. Before the next deployments, though, the carrier orbit relative to the first two microspacecraft is analyzed and adjusted as necessary. (Even if single ranging antennas on each spacecraft can not be used continuously in this process, the +Z antennas can be used in the vicinities of the orbital nodes.) The final microspacecraft pair is then deployed in a process similar to that used for the first pair. The last two carrier plane changes are then executed, in each case with orbit measurements and adjustments made relative to the other array spacecraft. (+Z antennas can at least be used when north-south positions are similar.)

Array Configuration Maintenance

At least three error sources (all involving potential period differences), need to be addressed in array configuration maintenance, these include:

Residual errors following array initialization and maintenance maneuvers
Orbit deterioration due to spatial variations in the lunar gravity field[2]
Differences in the gravity fields experienced by different spacecraft

The first of these is an obvious error source and has been discussed earlier; the other two are more subtle. Variations in the lunar gravity field have been shown to be capable of causing severe orbit deterioration.[2] For example, a spacecraft with an initial 10°, 100-km orbit has impacted the Moon in 35 days[2]. Orbits with lower inclination and higher altitude are more stable[2], and that is why they are used in this mission. Still, orbit deterioration might be significant enough to require frequent orbit maintenance maneuvers. Even if orbit altitudes are adequately stable and require no maneuvers, the gravity fields experienced by different spacecraft will be somewhat different. This can clearly be the case for spacecraft in different orbital planes, but it can also be the case for spacecraft that are in the same orbit. At first it might appear that spacecraft in the same orbit will see exactly the same gravity field variations but with a constant time offset. Actually, though, the time offset can cause them to see a slightly different field variation, because the Moon is slowly rotating under the inclined orbit. Both the use of different orbital planes and the lunar rotation might result in the need for maneuvers to maintain an adequate array configuration.

It would be desirable to hold down the frequency of required tracking from Earth and the amount of labor needed in array configuration maintenance. If the error sources discussed above would require excessive involvement from Earth, one or more of the following options could be used: increasing nominal orbital altitudes, reducing the final carrier orbit inclination, and implementing autonomous position maintenance.

TCM ΔV Allocation

As in the RAM mission concept, the Lunar Prospector mission[3] also used a STAR 37FM injection stage and had a very similar trans-lunar injection ΔV requirement. Since the TCM ΔV required to correct any injection ΔV error grows with time after injection, the mission planned a very early TCM, 4.5 hours after injection. (Offsetting this benefit, however, was a somewhat inefficient means of directing the net thrust vector, i.e., axial and tangential thrusters were fired in a vector mode to provide the desired resultant thrust vector.) The launch and injection ΔV magnitude error was calculated as 9.1 m/s, which would have required a 38 m/s TCM at 4.5 hours. Problems delayed the first TCM until 8.5 hours after injection, however, and increased the required ΔV magnitude to 50.2 m/s. A second TCM took place on schedule a day after the first TCM and provided 7.4 m/s. So, the total Lunar Prospector ΔV required to correct the 9.1 m/s injection error was 57.6 m/s (not counting the inefficiencies of its vector mode).

In the basic RAM mission concept, launch and injection error as high as 17 m/s can be handled with a first TCM as late as 12 hours after injection and TCM total ΔV capability of 95 m/s. (Also, the main engines are pointed in the desired thrust direction to eliminate the inefficiency associated with vector-mode burns.) Launch and injection errors even larger than 17 m/s and requiring more than 95 m/s TCM ΔV can be accommodated by lowering the inclination of the final carrier orbit plane (to balance out the earlier extra propellant use).

Example Other Use of Key RAM Hardware

A transponder/amplifier, cold gas/vapor microthrusters, and 3-axis microgyros that were nearly identical to those in this design concept were also included (and were also enabling elements) in a design concept for the Multimission Space and Solar Physics Microspacecraft, a concept involving multiple solar orbiters.[4]

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